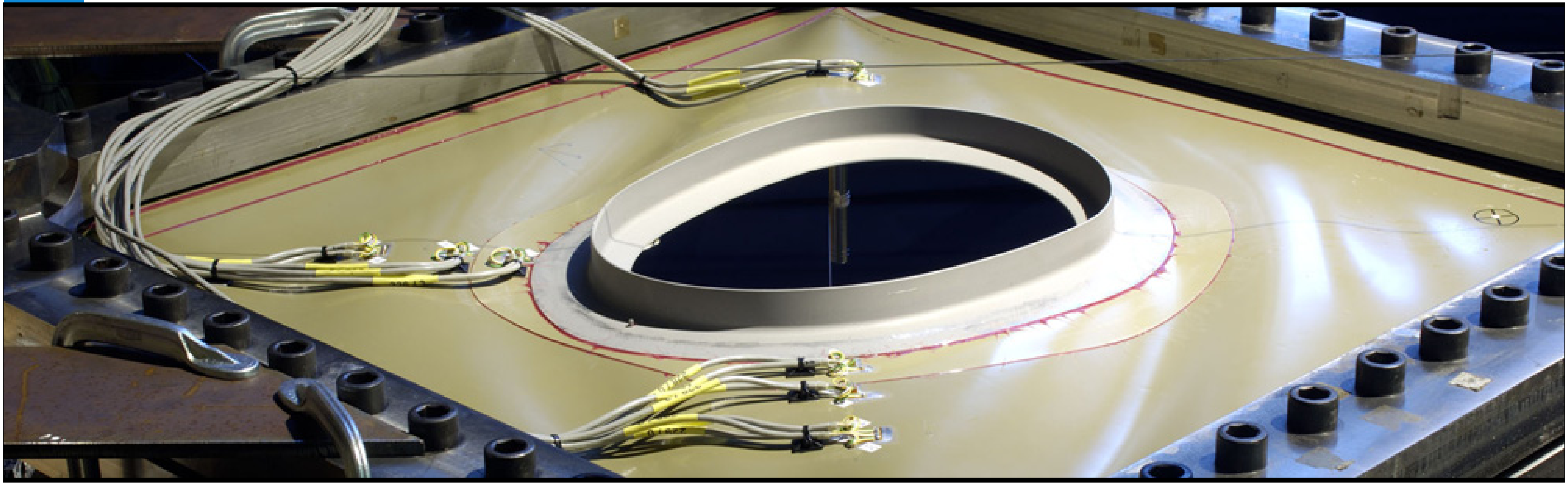
Damage Tolerance Philosophy for Bonded Aircraft Structures

Towards a generic assessment approach



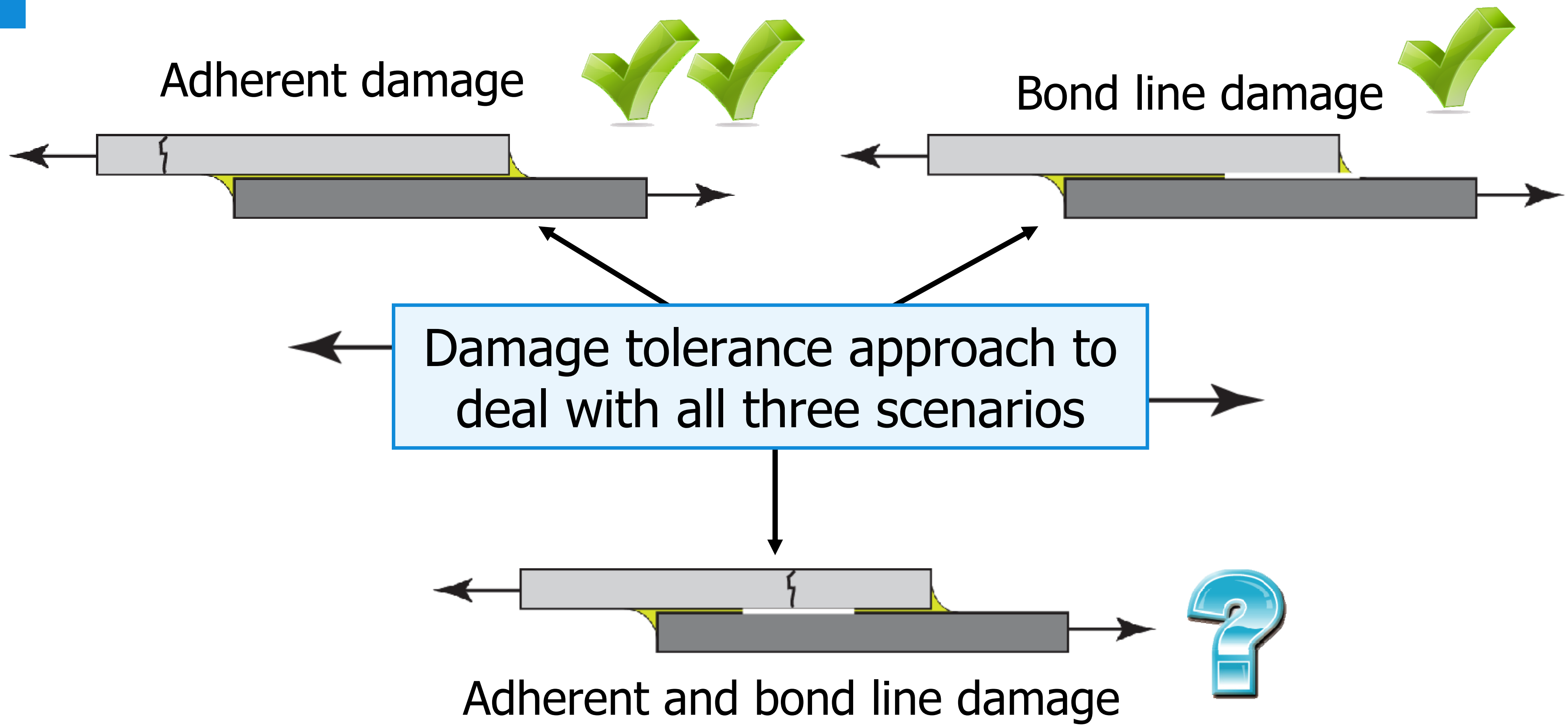
Dr. C.D. Rans

27-05-2009

Aerospace Materials
Faculty of Aerospace Engineering

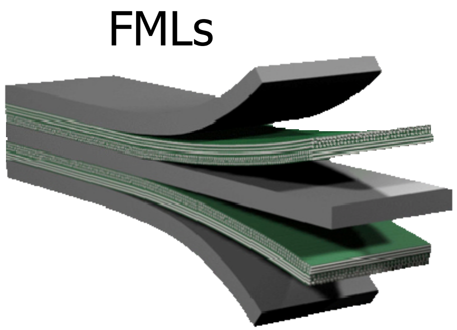
Possible Damage Scenarios

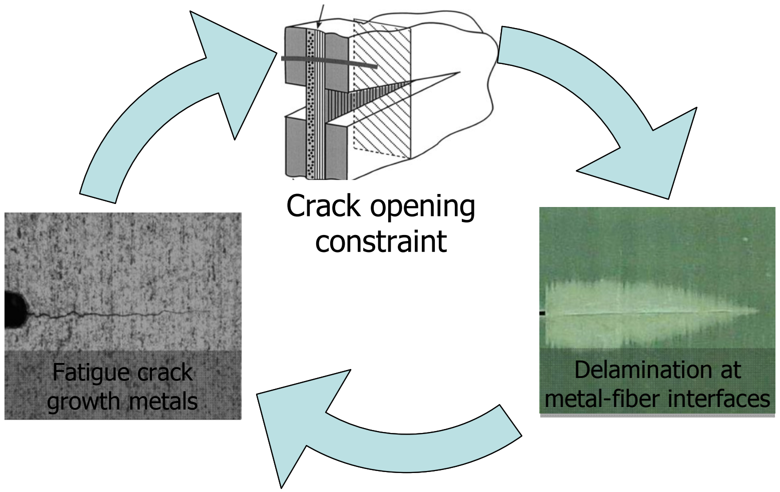
Generic Bonded Structure

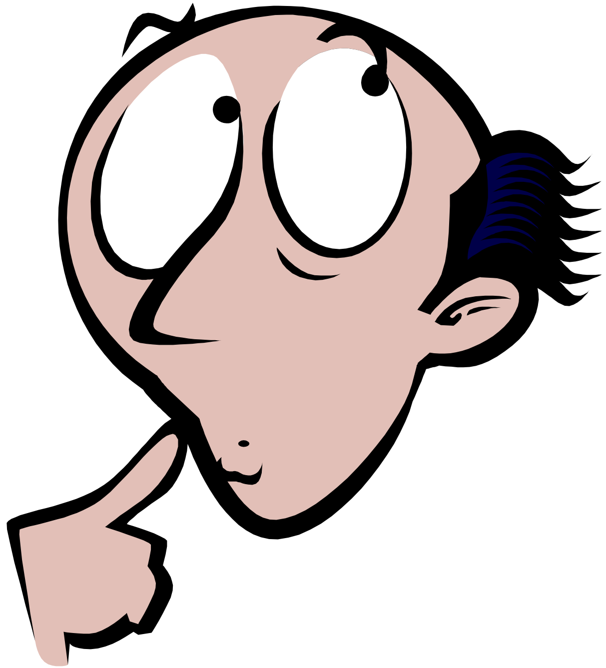


I Have Seen This Before!

Coupled Adherent and Bond Line Damage







Can this be translated to generic bonded structures?

1.

Prediction Approach

What Do We Need?

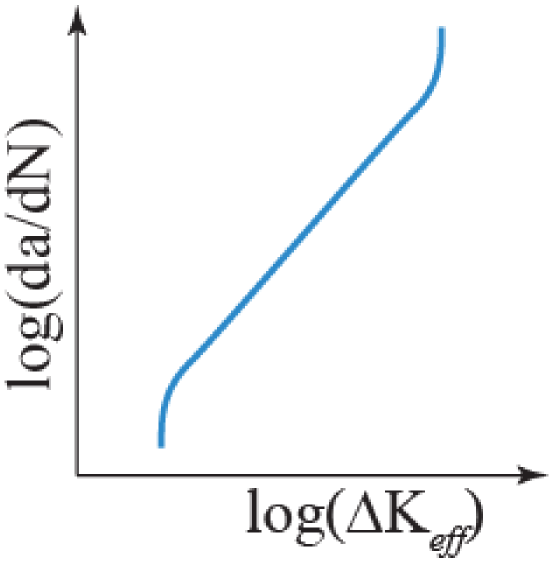
Required Prediction Approaches

- Bond line delamination growth
- Adherent damage growth
- Damage interaction

Adherent Crack Growth

Prediction Approach

- Fracture Mechanics description using Paris type relation
  - Mode I crack growth
  - Empirical relation for R-ratio effects



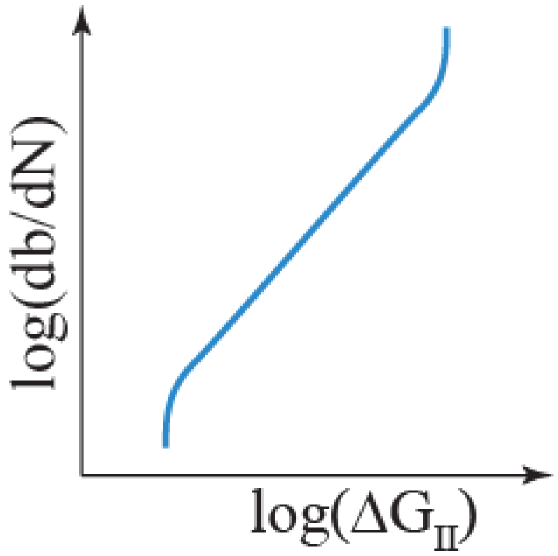
$$\frac{da}{dN} = C_{cg} (\Delta K_{eff})^{n_{cg}}$$

$$\Delta K_{eff} = \left(0.55 + 0.33R + 0.12R^2\right)\left(1 - R\right) K_{max}$$

Bond Line Delamination Growth

Prediction Approach

- Fracture Mechanics description using Paris type relation
  - Mode II delamination growth
  - Reformulated strain energy release rate range



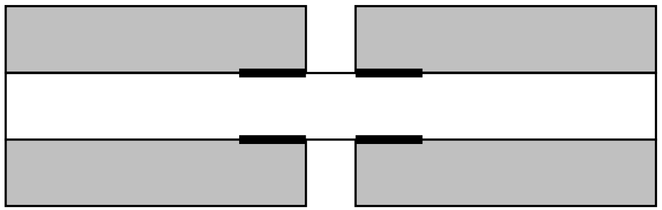
$$\frac{db}{dN} = C_d (\Delta G_{II})^{n_d}$$

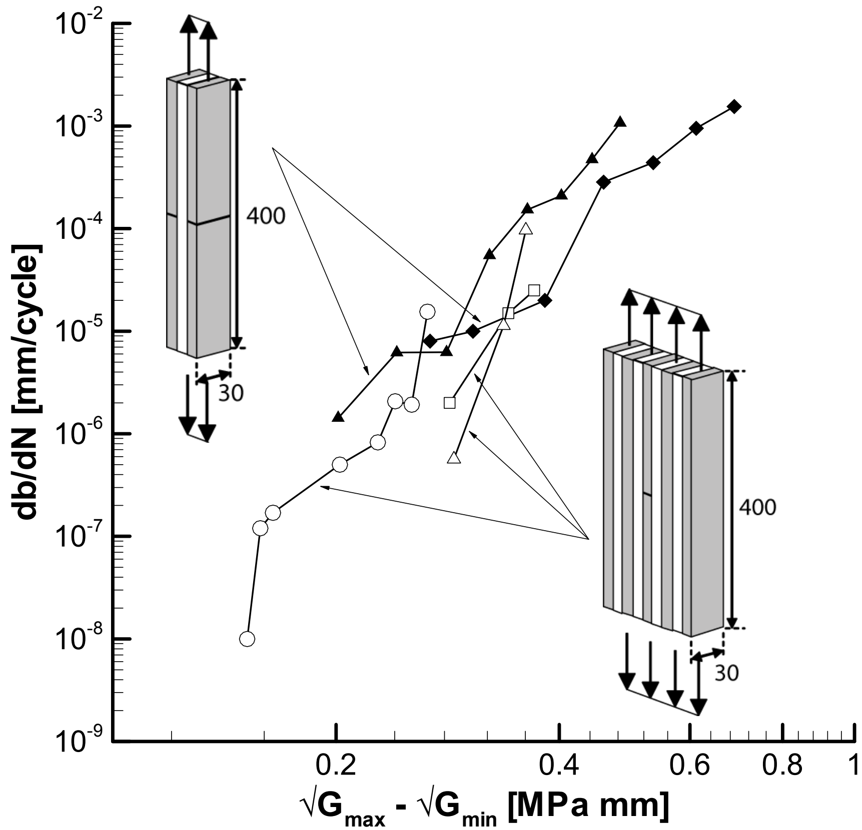
$$\Delta G_{II} \neq G_{II_{max}} - G_{II_{min}}$$
$$= \left(\sqrt{G_{II_{max}}} - \sqrt{G_{II_{min}}}\right)^2$$

Mode II Growth Assumption

Bond Line Delamination Growth

- Adhesive joints designed to transfer load through shear
- Mode II assumption supported by test data
  - FML delamination characterization
  - Composite laminates
- Damage growth, not initiation





Data obtained from Alderliesten et al. (2006)

Strain Energy Release Rate Range

Bond Line Delamination Growth

- Linear elastic fracture mechanics description
  - Principle of Similitude
  - Principle of Superposition

$$G_T = G_I + G_{II} + G_{III}$$

$$G_I = \left[\sqrt{G_{I(1)}} + \sqrt{G_{I(2)}} + \sqrt{G_{I(3)}} + \cdots \right]^2$$

$$G_{II} = \left[\sqrt{G_{II(1)}} + \sqrt{G_{II(2)}} + \sqrt{G_{II(3)}} + \cdots \right]^2$$

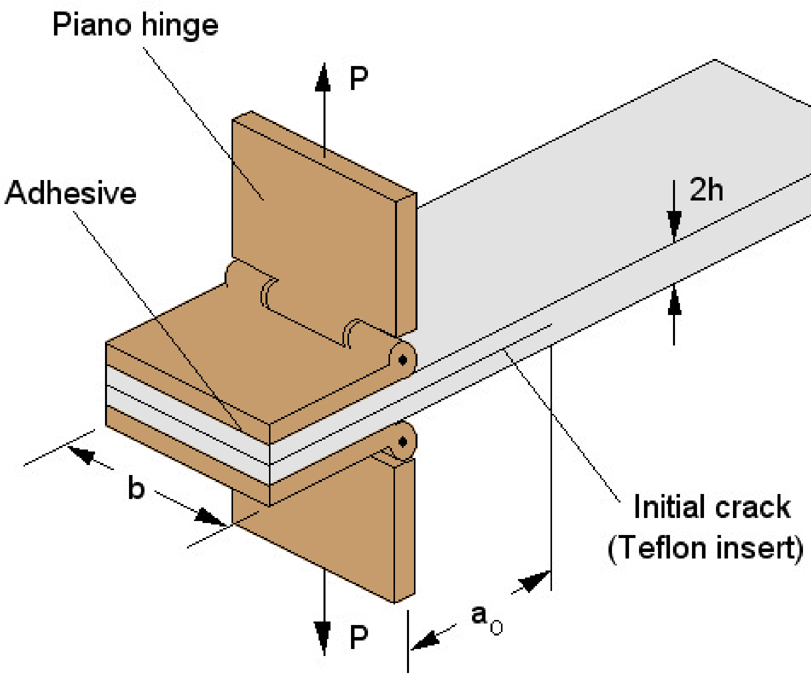
$$G_{III} = \left[\sqrt{G_{III(1)}} + \sqrt{G_{III(2)}} + \sqrt{G_{III(3)}} + \cdots \right]^2$$

$$\Delta G_{II} \neq G_{II_{\max}} - G_{II_{\min}} = \left(\sqrt{G_{II_{\max}}} - \sqrt{G_{II_{\min}}} \right)^2$$

Strain Energy Release Rate Range

Bond Line Delamination Growth

- Illustrate with Mode I DCB specimen



$$G_I = \frac{P^2}{2b}\frac{dC}{da}$$

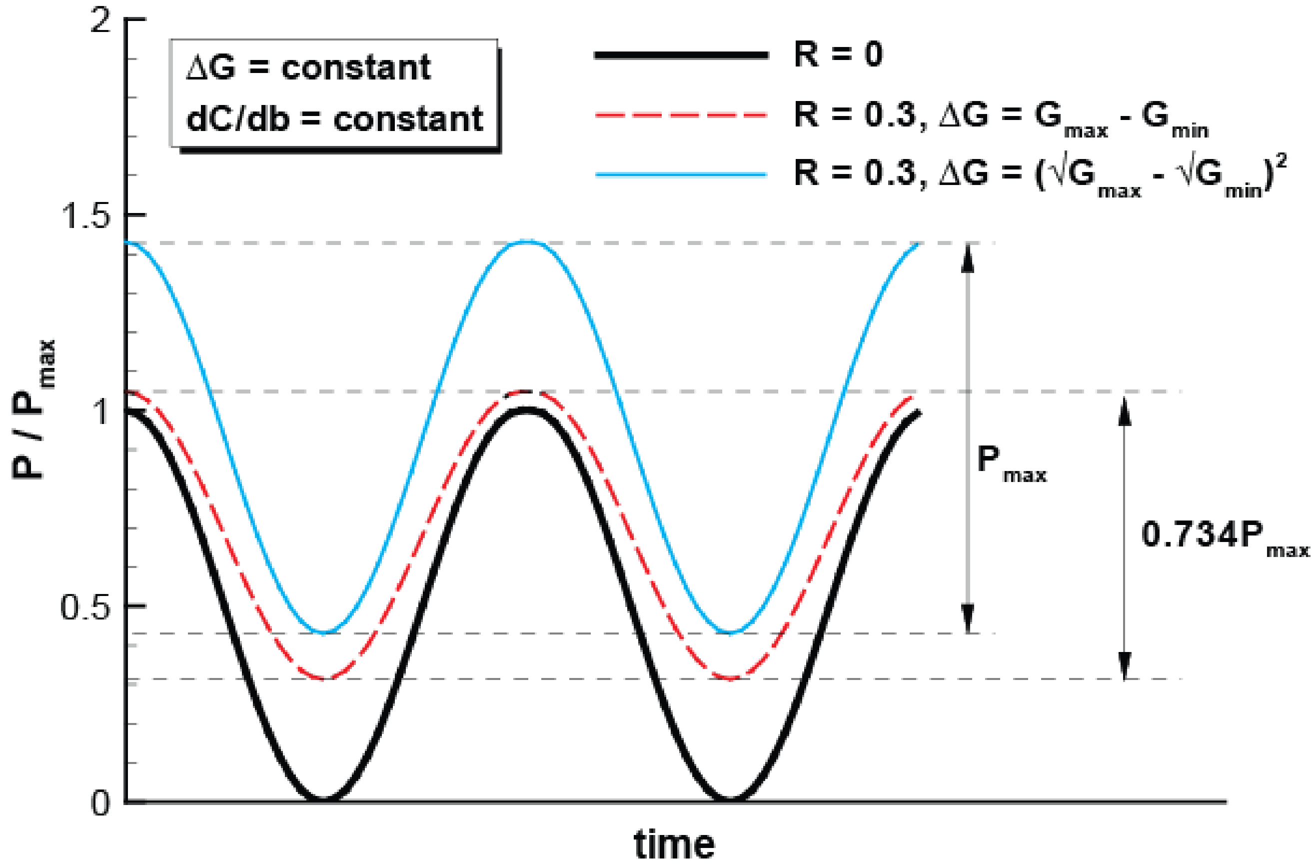
For identical crack and specimen geometries

$$G_I = const \cdot P^2$$

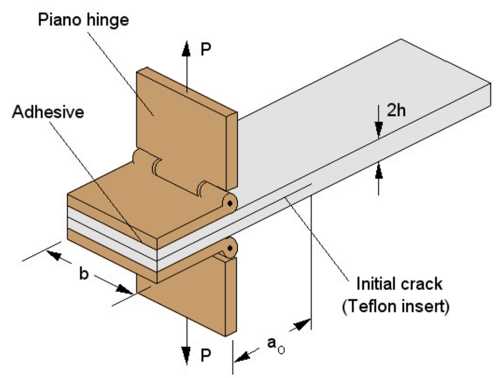
Compare applied loading to obtain the same ΔG for 2 different R-ratios

Strain Energy Release Rate Range

Bond Line Delamination Growth



$$G_I = const \cdot P^2$$

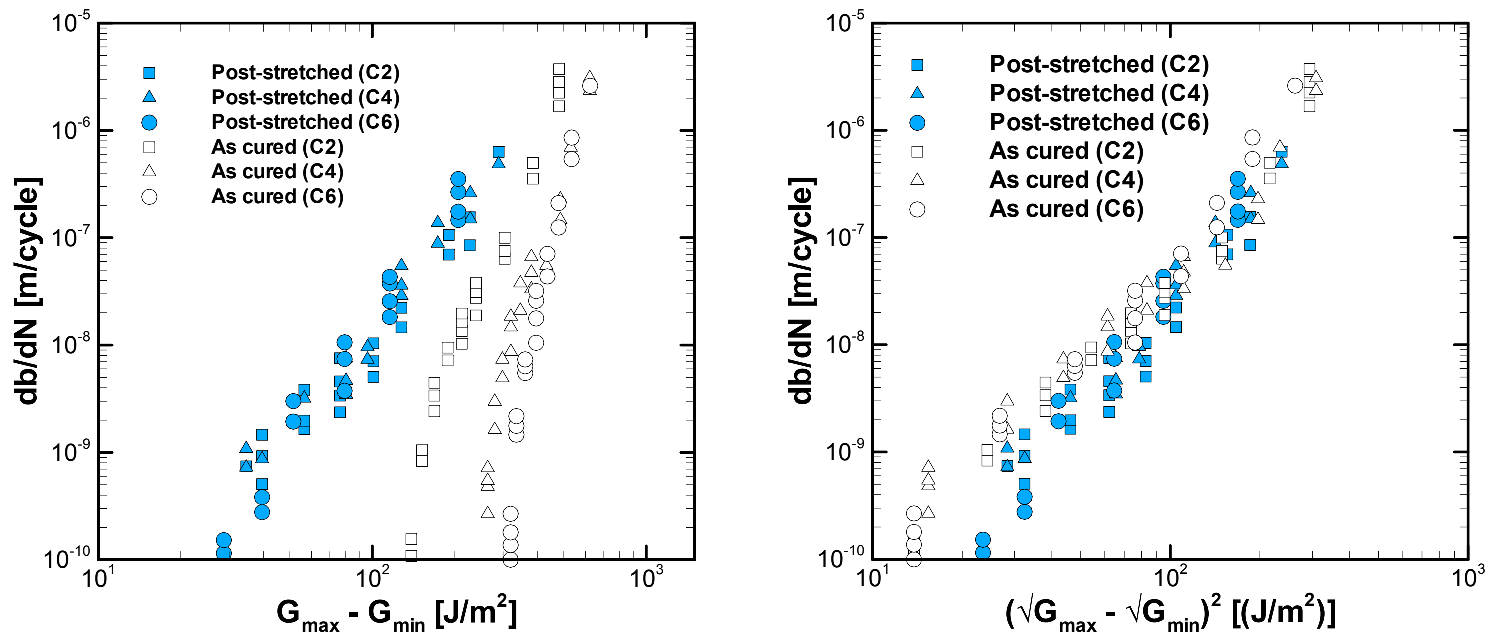


Strain Energy Release Rate Range

Bond Line Delamination Growth

- Advantages of new formulation
  - Removal of residual stress influence on SERR range
  - Permits use of superposition in analysis
  - R-ratio effects can be studied

Data obtained from Lin and Kao (1996)



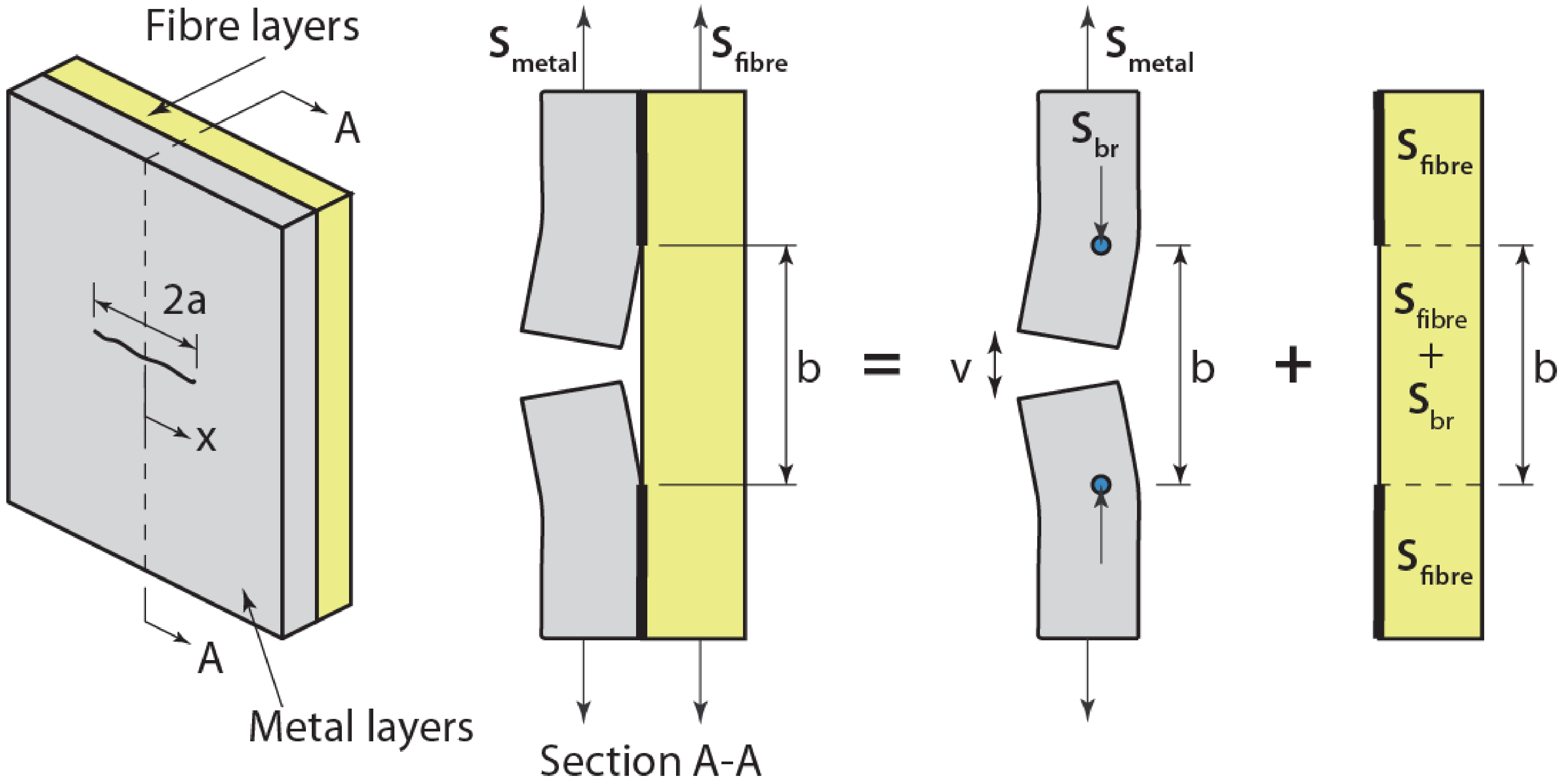
Damage Interaction

Prediction Approach

- Discretize damage area
- Enforce displacement compatibility between adherents
- Determine load redistribution resulting from damages
- Superposition of load redistribution on damage growth

Displacement Compatibility

Damage Interaction



Displacement Compatibility

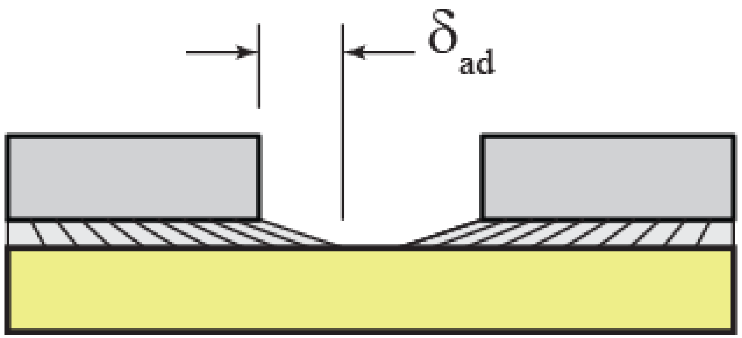
Damage Interaction

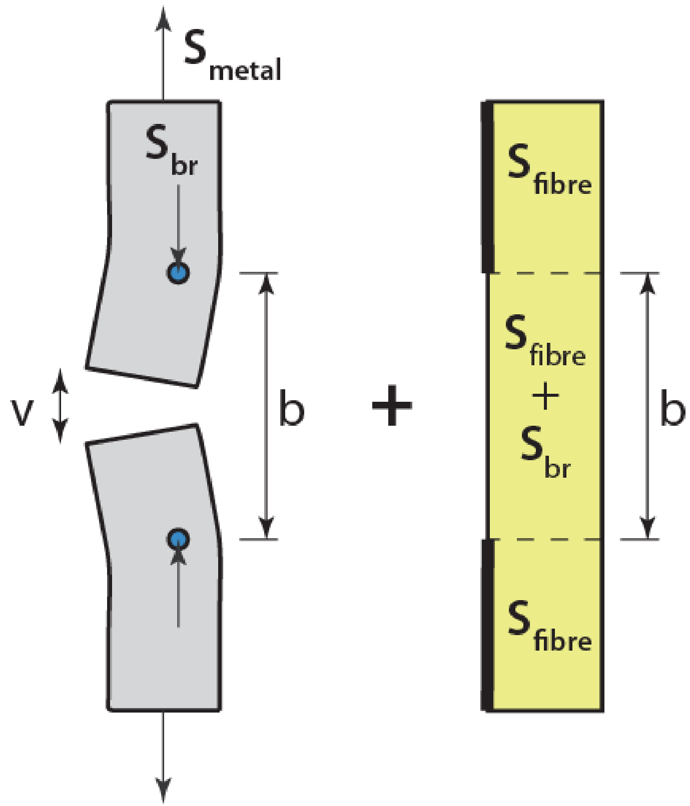
- Cracked adherent

$$v = v_{P_1} - v_{P_{br}}$$

- Undamaged adherent

$$\delta = \delta_{P_2} + \delta_{P_{br}} + \delta_{ad}$$





Over delamination length, b

$$v = \delta \rightarrow P_{br}$$

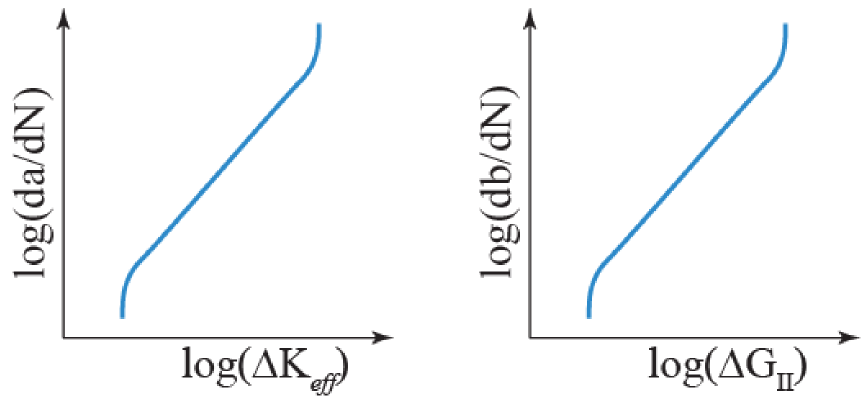
Influence on Damage Growth

Damage Interaction

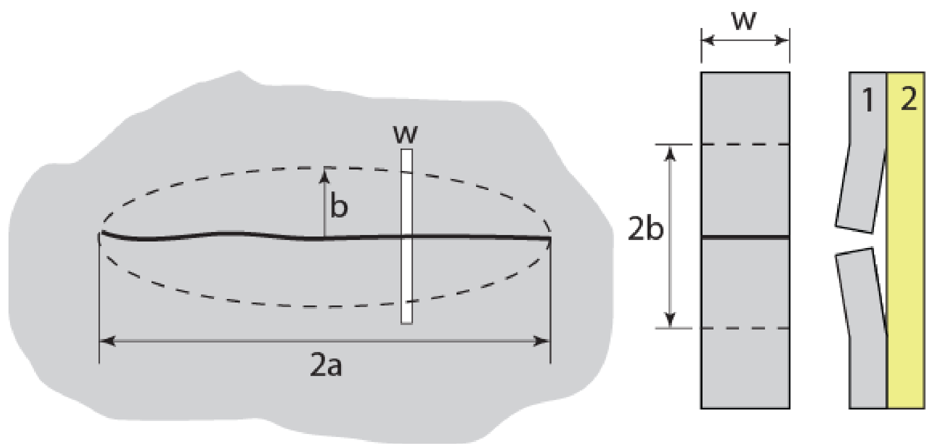
- Superposition of bridging load

$$K = K_{P_1} - K_{P_{br}}$$

$$G = f(P_1, P_2, P_{br})$$



- Implementation
  - Analytical solutions
  - FEM



Discretization into 1-D damage interaction zones

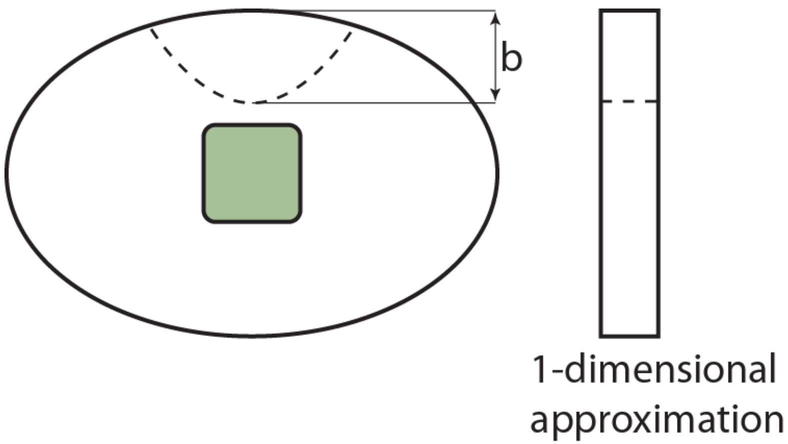
2.

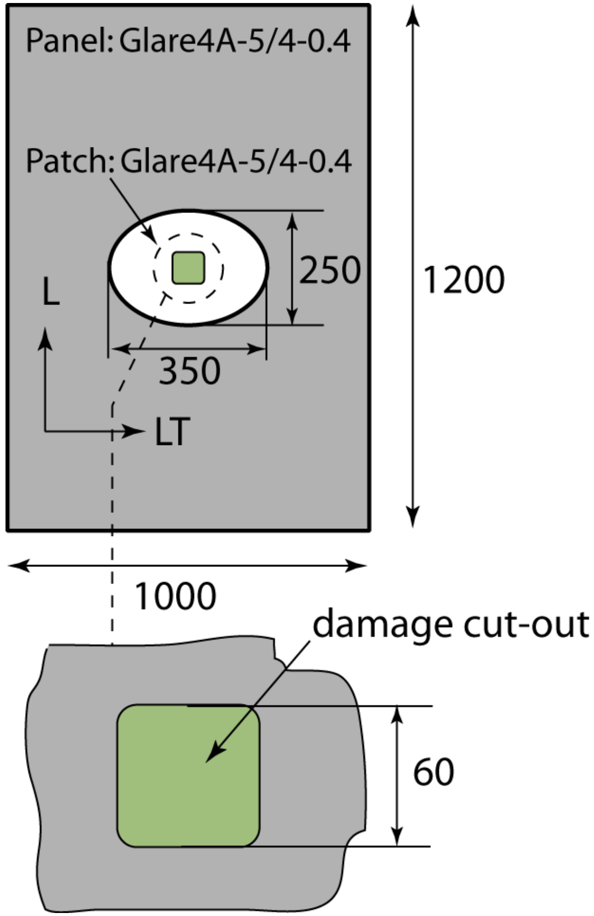
Case Studies

Bonded Patch Repair

Case Studies

- Predict edge delamination growth behaviour
  - Adherents undamaged
  - Delamination growth model only
- Initiation assumed at 1st load cycle
- Approximate as a 1-D problem

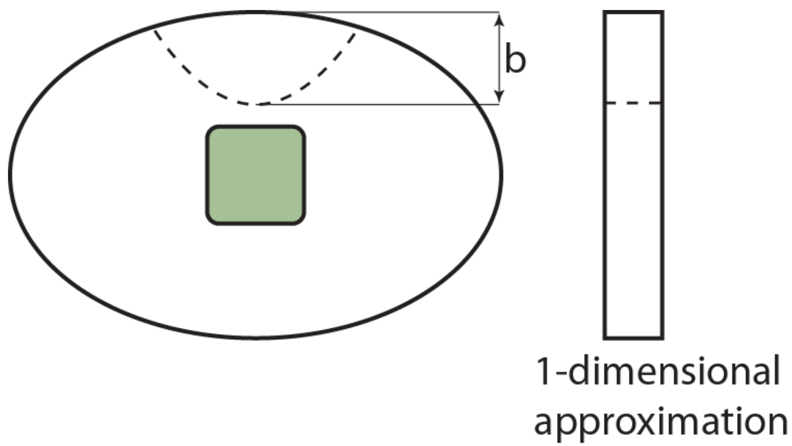


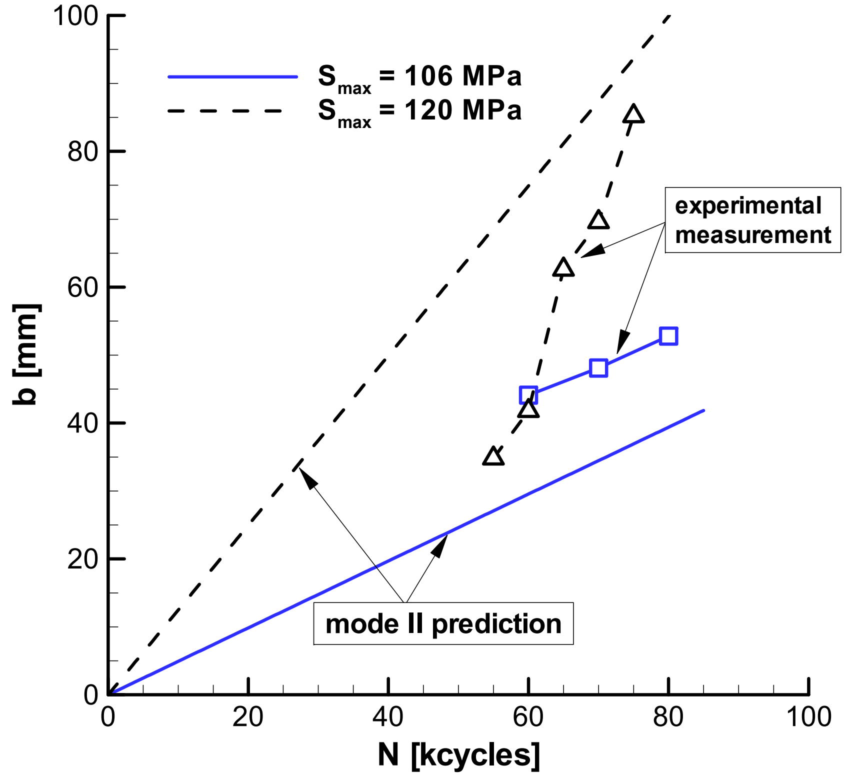


Bonded Patch Repair

Case Studies

- Good agreement in damage growth rates
- Shift in data due to damage initiation behaviour





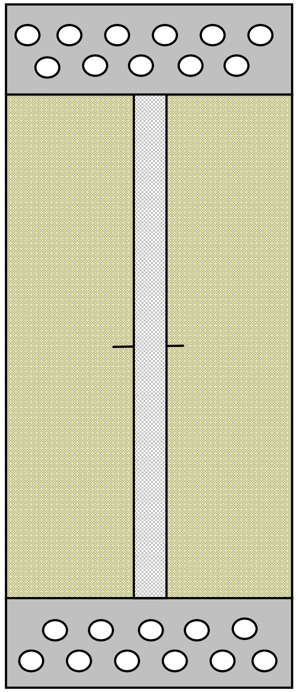
FML Panel with a Bonded Strap

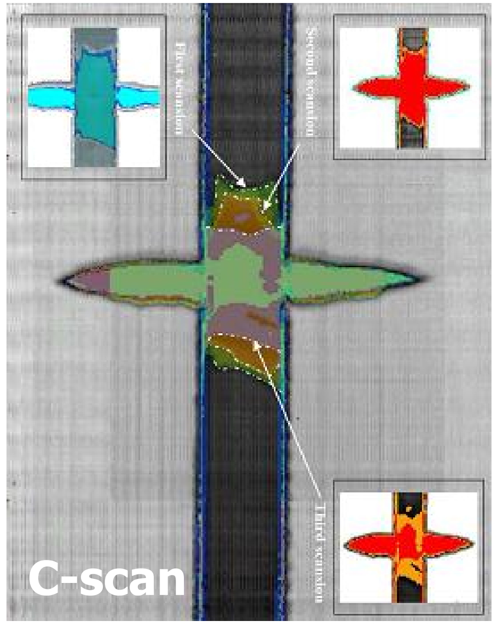
Case Studies

- Cracked Glare panel with an intact bonded titanium strap
- Damages
  - Cracked metal layers of FML
  - Delamination between metallic and fibre FML layers
  - Delamination between strap and FML
- Superposition of multiple bridging effects

$$K = K_{farfield} - K_{br,FML} - K_{br,stiffner}$$

$$G_{FML}, G_{stiffener}$$

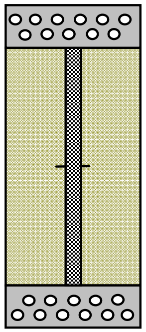




FML Panel with a Bonded Strap

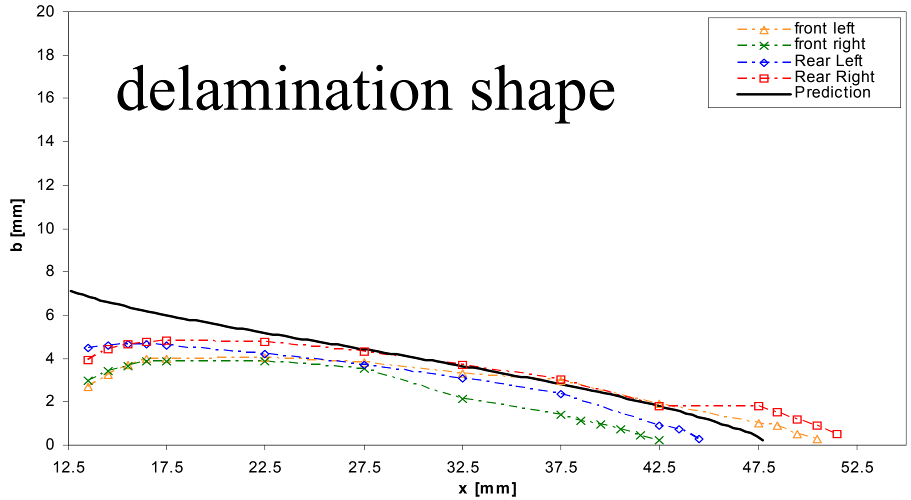
Case Studies

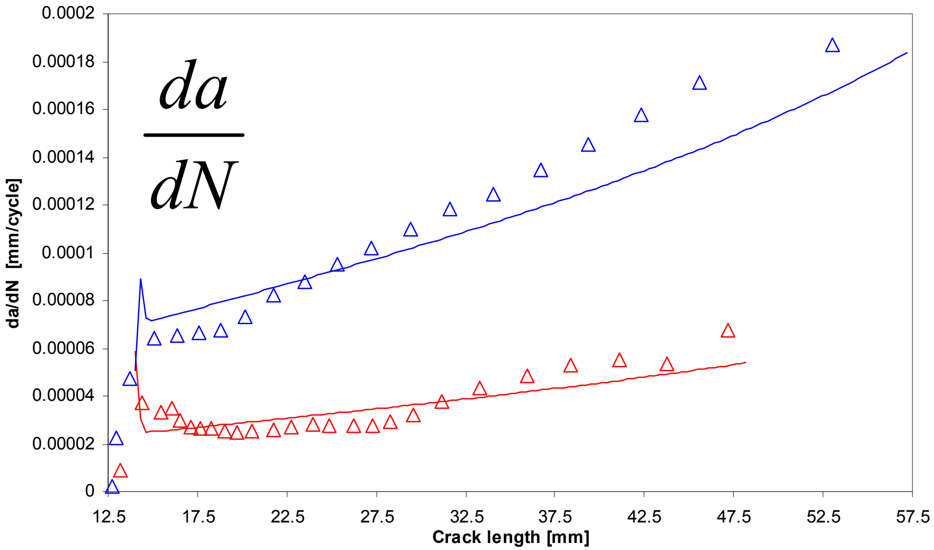
- Prediction

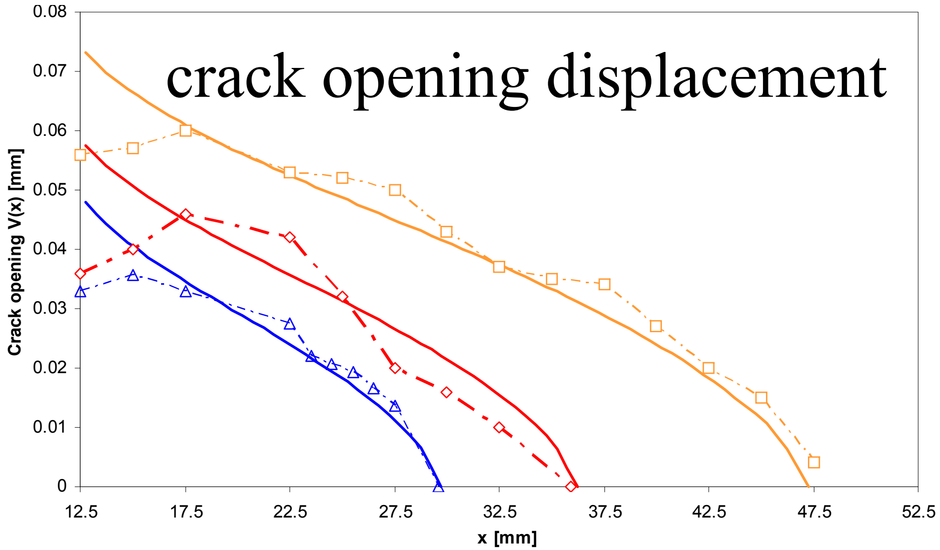


Intact central strap

Data obtained from Rodi (2007)



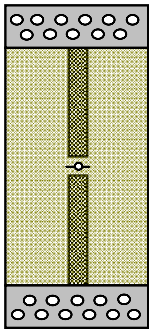




FML Panel with a Bonded Strap

Case Studies

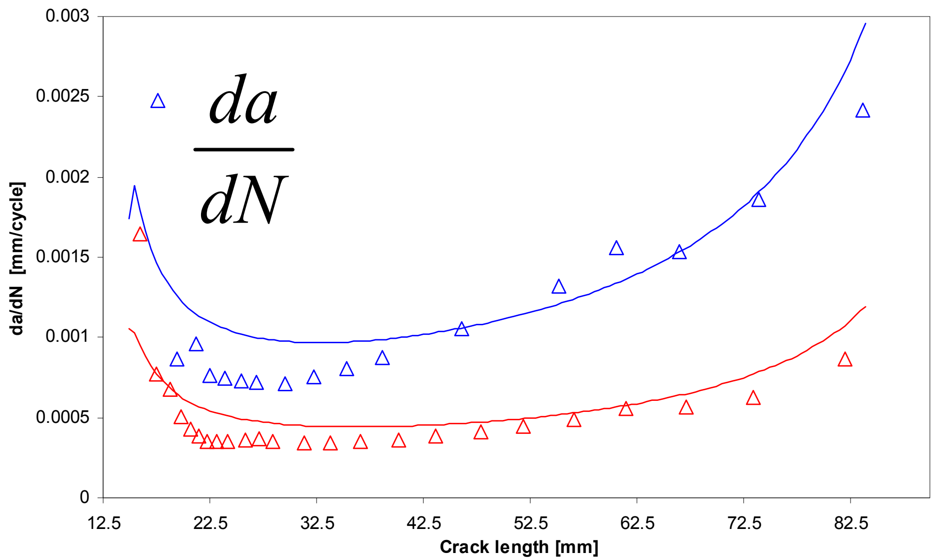
- Prediction

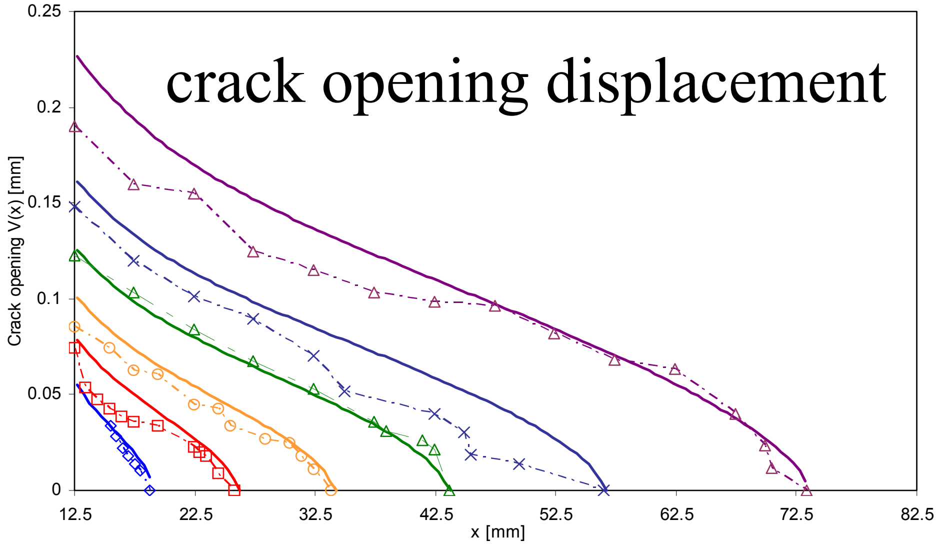


Broken central strap

$$K = K_{farfield} - K_{br,FML} + K_{br,stiffner}$$

Data obtained from Rodi (2007)





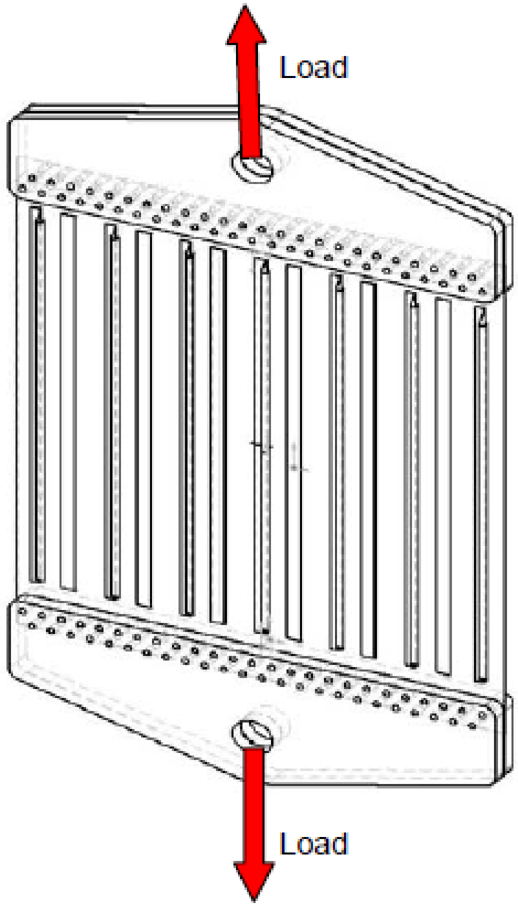
Metallic Skin with Bonded Stiffeners

Case Studies

- Predict crack growth in stiffened panel
  - Aluminum skin
  - 7 bonded aluminum stringers
  - 7 bonded aluminum straps
  - Central stringer initially broken
- Stiffener failure assumption
- Superimpose bridging effects of all stringers

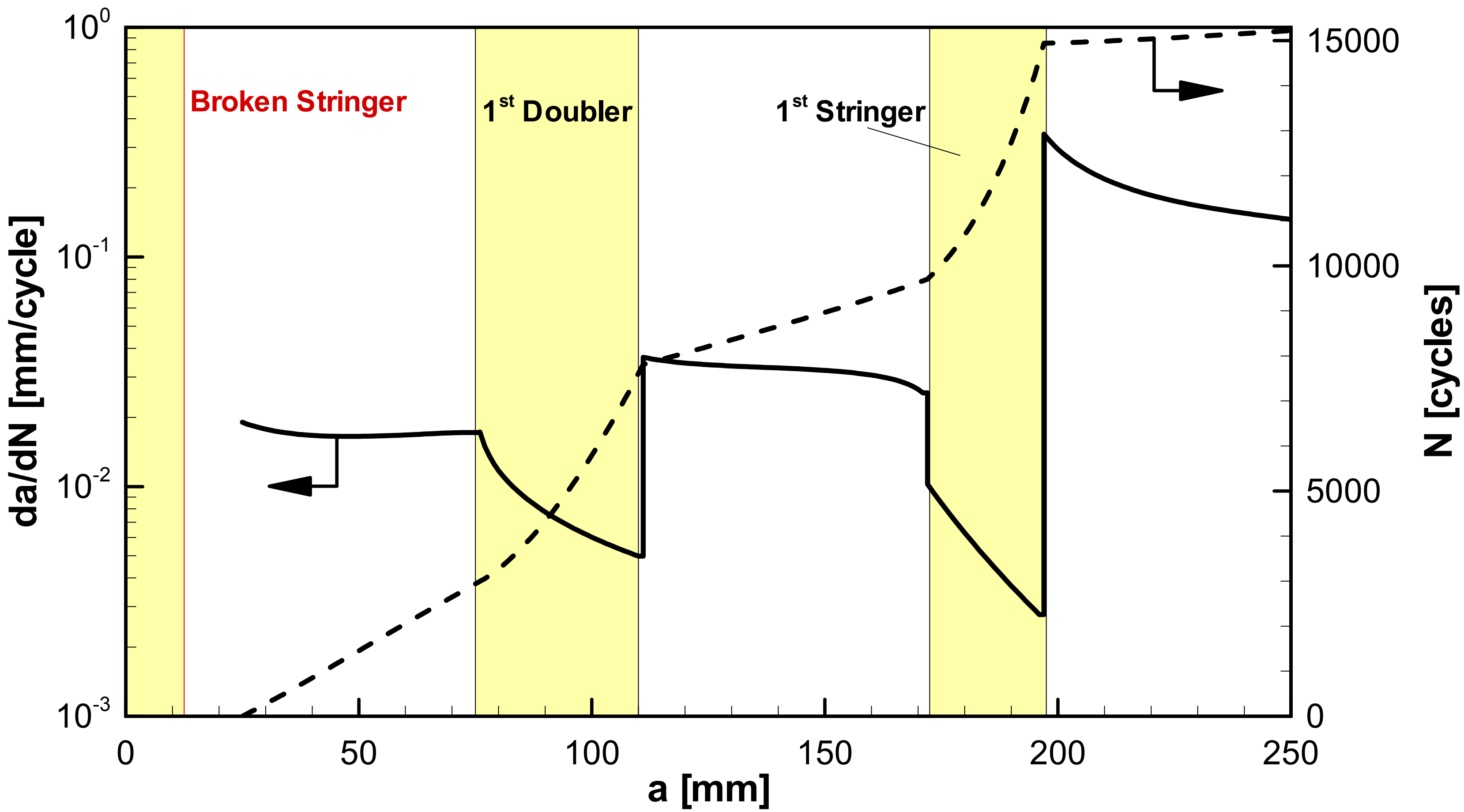
$$K = K_{farfield} + \sum K_{stiffeners}$$

$$G_{stiffner1}, \cdots, G_{stiffnerN}$$



Metallic Skin with Bonded Stiffeners

Case Studies



Summary

- Damage tolerance analysis philosophy
  - Simultaneous analysis of adherent and bond line damage
  - Linear elastic fracture mechanics description of damage growth
  - Damage interaction through displacement compatibility and superposition
- Philosophy demonstrated to work for bonded metallic and hybrid structures
  - Cracked metal adherents
  - Bond line delamination growth
  - Crack opening displacement

Summary

- Potential for composite structures
  - Stiffness reduction in damaged composite
  - Determination of load redistribution through displacement compatibility (superposition of effects)
  - Requires further work and understanding of composite damage growth
- Potential power of superposition and linear elastic fracture mechanics for delamination growth prediction
  - Proper formulation of SERR range

Questions?

References

- R.C. Alderliesten, J. Schijve, and S. van der Zwaag, *Application of the SERR approach for delamination growth in Glare*. Eng. Fract. Mech., **73**(6), 2006, pp. 697-709.
- C.T. Lin and P.W. Kao, *Delamination growth and its effects on crack propagation in carbon fibre reinforced aluminum laminates under fatigue loading*. Acta Mater., **44**(3), 1996, pp. 1181-88.
- R. Rodi, *The effect of external stiffening elements on the fatigue crack growth in Fibre Metal Laminates*. Masters thesis, 2007, Delft University of Technology, Delft, the Netherlands